Demonstration of Turbulence Resiliency in a Mode-, Polarization-, and Wavelength-Multiplexed Free-Space Optical Link using Pilot Tones and Optoelectronic Wave Mixing

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Abstract *We experimentally demonstrate the turbulence resiliency in a mode-, polarization, and wavelength- multiplexed free-space optical link using pilot tones and optoelectronic wave mixing. 8 multiplexed channels combined with 2 OAM modes, 2 polarizations, and 2 wavelengths are demonstrated in a 4-Gbit/s QPSK link.*

Introduction

There is growing interest in free-space optical (FSO) communication links due partially to the increased demand for data capacity [1,2]. Moreover, it has been shown that capacity can be further increased by mode-division-multiplexing (MDM), which is a subset of space-division-multiplexing (SDM) [3,4]. In MDM systems, multiple independent data-carrying beams are simultaneously transmitted, and each beam is structured to have a different orthogonal mode [5]. Such orthogonality enables efficient multiplexing, spatial co-propagation, and demultiplexing with little inherent crosstalk [6,7]. One example of a modal basis set is orbital-angular-momentum (OAM), which is a subset of Laguerre Gaussian (LG) modes [8]. Each OAM-carrying beam typically has a ring intensity profile and the mode value l is the number of 2π phase shifts in the azimuthal direction [9]. A key challenge in MDM links based on OAM is atmospheric turbulence, which can induce phase distortion to the beam, power coupling to other modes, and deleterious data channel crosstalk [10].

Recently, an approach was reported that enabled some degree of resiliency to turbulence [11,12]. Specifically, the experimental technique had the following elements: (a) a data channel and a pilot tone were transmitted on the same mode and polarization through a similarly turbulent medium but located on different wavelengths, (b) the data and tone mix together in an optoelectronic detector, and (c) the resultant signal-pilot tone mixing product is resilient to modal power coupling [12]. This resilience is a result of the wave mixing in the detector, such that the coupling matrix and its conjugate are both produced and multiplied together, thereby mitigating the turbulence. Given that optical communication systems often use other forms of multiplexing, such as polarization and wavelength multiplexing, it may be desirable to extend this technique to accommodate multiple

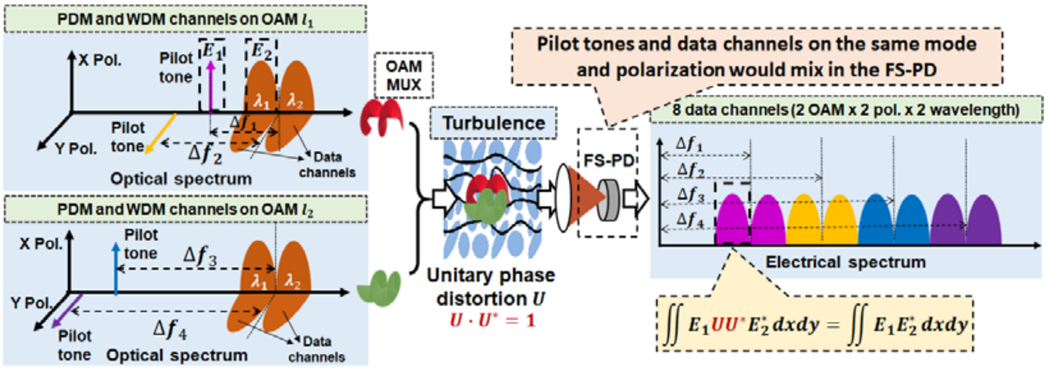

Fig. 1: Concept of the turbulence resilient link combining OAM ($l_1$and l_2), polarization (pol. X and Y) and wavelength (λ_1 and λ_2) multiplexing. For each OAM mode, two pilot tones are located at different polarizations with different Δf. The turbulence-induced distortions are "canceled" using the pilot tone-data mixing in a free space photodetector (FS PD).

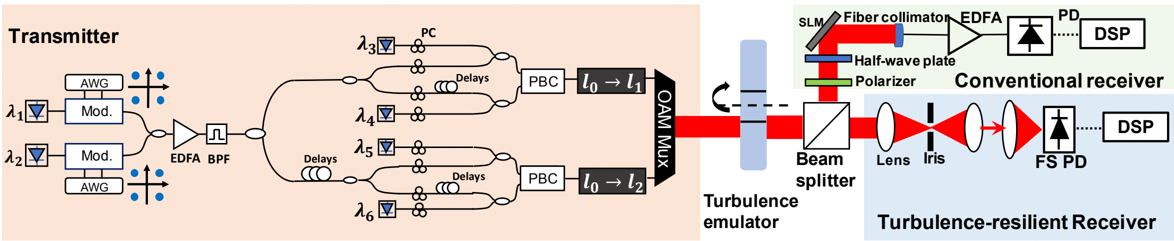

Fig. 2: Experimental setup. λ_1 and λ_2 are modulated for two wavelength multiplexed data channels. λ_1, λ_2, λ_3 and λ_4 are four pilot tones. A glass phase plate is used as the turbulence emulator. At the conversional receiver, a polarizer is used to separate polarizations and a spatial light modulator (SLM) is used to separate OAM modes. PC: polarization controller; AWG: arbitrary waveform generator; EDFA: Erbium-doped fiber amplifier; BPF: band pass filter; PBC: polarization beam combiner.

multiplexing domains simultaneously.

In this paper, we experimentally demonstrate turbulence resiliency in a mode-, polarization-, and wavelength-multiplexed FSO link using pilot tones and optoelectronic wave mixing. By transmitting different pilot tones on different polarization and modes, the polarization and mode multiplexed data channels could be selected during the optoelectronic mixing. By properly choosing the frequency spacing between pilot tones and data channels, data channels can be down-converted to different frequencies and separated with little turbulence-induced crosstalk. A 4Gbit/s quadrature phase-shift keying (QPSK) turbulence-resilient link is demonstrated with combined 2 OAM (*l*=+1 & *l*=-2), 2 polarization and 2 wavelength multiplexing. With stronger turbulence, the error vector magnitudes (EVM) of the received 8 data channels degrades are up to 29.1%, while are measured to be >40% using the conventional receiver.

Concept

Figure 1 shows the concept of the turbulence resilient link combining OAM, polarization, and wavelength multiplexing. At the transmitter, for each OAM mode (l_1 or l_2), independent data channels located at different wavelength ($\boldsymbol{\lambda}_1$ and $\boldsymbol{\lambda}_2$) and different polarization (pol. X and pol. Y) are multiplexed. Two pilot tones on two polarizations are added with frequency difference $\Delta\boldsymbol{f}$ ($\Delta\boldsymbol{f}_1$ and $\Delta\boldsymbol{f}_2$ for OAM l_1, and $\Delta\boldsymbol{f}_3$ and $\Delta\boldsymbol{f}_4$ for OAM l_2) compared with the data channels. After OAM multiplexing, the pilot and data channels of the same OAM mode are likely to experience the similar turbulence-induced unitary spatial phase distortion $\boldsymbol{U}(\boldsymbol{x},\boldsymbol{y})$. After propagating through the turbulent atmosphere, the beam spatial profiles of the OAM beam carrying both the pilot and multiplexed data channels are focused on a free-space photodetector (FS-PD). At the receiver, the FS-PD would mix the similarly distorted pilot-carrying and data-carrying beams with the same polarization and same OAM mode, and generate signal-pilot beating terms at different frequency Δf in the electrical domain, e.g. $\iint \boldsymbol{E}_1\ \boldsymbol{U}\boldsymbol{U}^*\ \boldsymbol{E}_2^*\ \boldsymbol{dxdy}$=$\iint \boldsymbol{E}_1\ \boldsymbol{E}_2^*\ \boldsymbol{dxdy}$. The turbulence-induced unitary phase distortion is being cancelled since $\boldsymbol{U}\boldsymbol{U}^*$ =1, which enables the turbulence resiliency of data channels. By choosing the proper frequency spacing $\Delta\boldsymbol{f}$, data channels can be down-converted to different frequencies and separated with little turbulence-induced crosstalk. The different data channels are detected by heterodyne detections. Digital signal processing (DSP) algorithms are applied to retrieve the data information of the data channels.

Experiment

Figure 2 shows the experimental setup. At the transmitter, two different carriers ($\boldsymbol{\lambda}_1$ and $\boldsymbol{\lambda}_2$) are modulated with 0.25-Gbaud QPSK signals independently and multiplexed. After pre-amplification, the wavelength-multiplexed data channels are split into four parts, and their polarizations are intendedly controlled. Four pilot tones are combined with the data channels. Polarization beam combiners (PBC) are used to enable the polarization multiplexing. Two pilot tone and data combinations are converted into

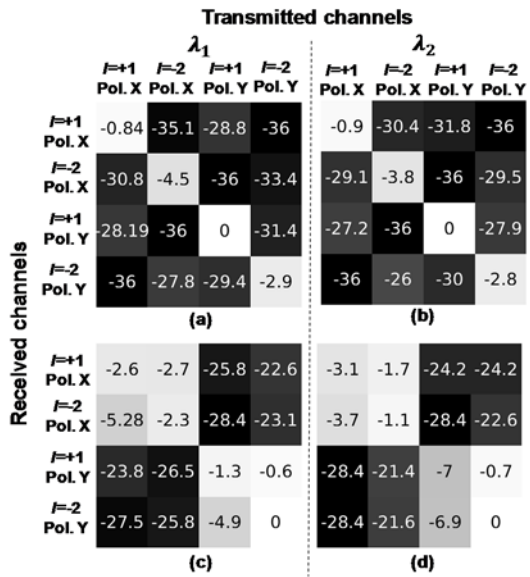

Fig. 3: Normalized crosstalk (in dB scale) between different data channels for λ_1 without (a) and with (c) turbulence and λ_2 without (b) and with (d) turbulence

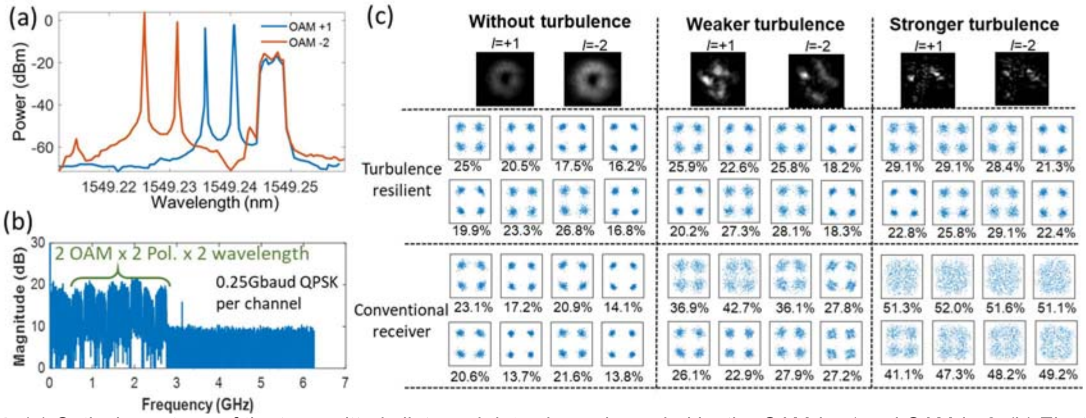

Fig. 4: (a) Optical spectrum of the transmitted pilots and data channels carried by the OAM *l=+1* and OAM *l=-2*. (b) Electrical spectrum with 8 received data channels after the wave mixing of the pilot tone and data. (c) Beam profiles, data channel constellations and EVM performance (under the corresponding constellations) of the turbulence-resilient and conventional receiver

OAM modes l_1 and l_2. A glass phase plate is used to emulate the turbulence effects with Fried parameter r_0=0.4 mm (stronger) and 1 mm (weaker). At the receiver, the proposed turbulence-resilient receiver using pilot tone-data mixing approach and conventional receiver are compared. The 3-dB bandwidth of the FS-PD (Thorlabs DET08C) is ~3GHz.

Figure 3 shows the normalized channel crosstalk with and without turbulence for data channels located at λ_1 and λ_2, respectively. The results indicate that, for both λ_1 and λ_2, the turbulence effects mainly induce the crosstalk between different OAM modes and little crosstalk (<-20dB) between different polarizations [13]. The pilot tones and data channels from different polarizations might experience little crosstalks, which maintains the turbulence resiliency of the pilot tone-data mixing approach when applying polarization multiplexing. Figure 4 (a) shows the optical spectrum of the pilot tones and data channels of the OAM *l*=+1 and OAM *l*=-2. The corresponding electrical spectrum with 8 data channels after pilot tone-data mixing is shown in Figure 4 (b). Figures 4 (c) shows the constellations and compares the error vector magnitude (EVM) performance of the turbulence-resilient receiver and conventional receiver with and without turbulence. The results show that the performance of the conventional receiver degrades quickly as the turbulence effects getting stronger. The turbulence-resilient receiver suffers much fewer degradations for all 8 data channels which indicates the turbulence resiliency of the OAM, polarization, and wavelength multiplexed link. Figure 5 (a) shows the bit error rate (BER) performance of the turbulence-resilient link. The result shows that the BER performance with turbulence is close to that without turbulence. The fluctuation of the BER among different channels might be due to the different responses of the FS-PD at different electrical frequencies. Figure 5 (c) compares turbulence resilient links using (i) OAM multiplexing, (ii) OAM & polarization multiplexing, and (iii) OAM, polarization, and wavelength multiplexing. The result shows that given the same total transmitted power and bit rate (4-Gbit/s), these three schemes have similar EVM performance.

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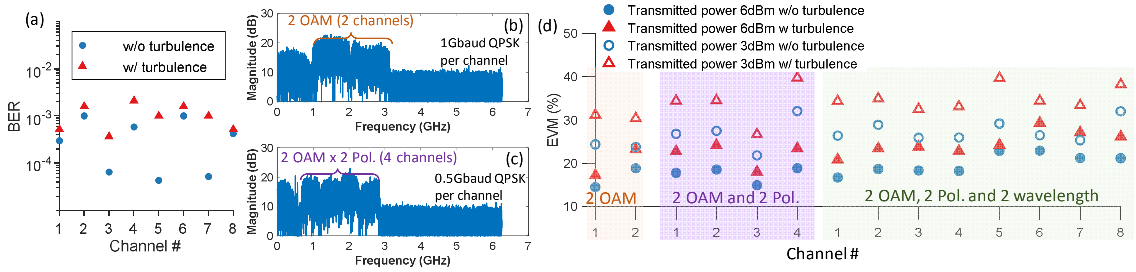

Fig. 5: (a) BER performance of the multiplexed 8 data channels when the transmitted optical power is 3dBm. Electrical spectrum of (b) two multiplexed OAM channels and (c) 2 multiplexed OAM channels and 2 polarization channels after pilot tone-data mixing. (d) EVM performance of different channels with and without turbulence

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